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# In Vivo Evaluation of the Potential of High-Frequency Ultrasound for Arthroscopic Examination of the Shoulder Joint

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## Abstract

**Objective.** Accurate arthroscopic evaluation of cartilage lesions could significantly improve the outcome of repair surgery. In this study, we investigated for the first time the potential of intra-articular ultrasound as an arthroscopic tool for grading cartilage defects in the human shoulder joint *in vivo* and compared the outcome to results from arthroscopic evaluation and magnetic resonance imaging findings. **Design.** A total of 26 sites from 9 patients undergoing routine shoulder arthroscopy were quantitatively evaluated with a clinical intravascular (40MHz) ultrasound imaging system, using the regular arthroscopy portals. Reflection coefficient (*R*), integrated reflection coefficient (*IRC*), apparent integrated backscattering (*AIB*), and ultrasound roughness index (*URI*) were calculated, and high-resolution ultrasound images were obtained per site. Each site was visually graded according to the International Cartilage Repair Society (ICRS) system. “Ultrasound scores” corresponding to the ICRS system were determined from the ultrasound images. Magnetic resonance imaging was conducted and cartilage integrity at each site was classified into 5 grades (0 = normal, 4 = severely abnormal) by a radiologist. **Results.** *R* and *IRC* were lower at sites with damaged cartilage surface ( $P = 0.033$  and  $P = 0.043$ , respectively) and correlated with arthroscopic ICRS grades ( $r_s = -0.444$ ,  $P = 0.023$  and  $r = -0.426$ ,  $P = 0.03$ , respectively). Arthroscopic ICRS grades and ultrasound scores were significantly correlated ( $r_s = 0.472$ ,  $P = 0.015$ ), but no significant correlation was found between magnetic resonance imaging data and other parameters. **Conclusion.** The results suggest that ultrasound arthroscopy could facilitate quantitative clinical appraisal of articular cartilage integrity in the shoulder joint and provide information on cartilage lesion depth and severity for quantitative diagnostics in surgery.

## Keywords

arthroscopy, ultrasound, cartilage, subchondral bone, shoulder

## Introduction

Clinical diagnostics of cartilage and subchondral lesions in the shoulder joint are currently performed via physical examination, and noninvasively by radiographic and magnetic resonance imaging (MRI). These methods are fairly poor in detecting lesions at their early stages. Conventional arthroscopic surgery is an invasive technique, but enables direct inspection of the cartilage surface. However, diagnosis of chondral defects in arthroscopy is based on qualitative and subjective visual appraisal, with subsurface changes in tissue structure often remaining undetectable. Furthermore, the outcome of arthroscopic evaluation is influenced by the operating surgeon’s experience, with the majority of experienced orthopaedic surgeons finding it difficult to distinguish between high- and low-grade cartilage damage,<sup>1,2</sup> indicating

the need for quantitative and objective measures of cartilage integrity.<sup>1</sup> In addition, the ongoing development of cartilage repair techniques and novel approaches for

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pharmacological intervention aiming at slowing down or reversing osteoarthritis progression requires more sensitive methods of visualising and quantifying the effectiveness of the treatments protocols *in vivo*.<sup>3,4</sup>

Ultrasound imaging has been proposed as a potential method to meet these needs.<sup>5-12</sup> With ultrasound, quantitative evaluation of articular cartilage integrity,<sup>11,12</sup> surface roughness and composition is possible.<sup>13-23,26</sup> We recently introduced an ultrasound arthroscopy technique for clinical assessment of articular cartilage and subchondral bone integrity.<sup>11</sup> In this technique, a high-frequency (40 MHz) intravascular ultrasound (IVUS) catheter is applied into the joint space under arthroscopic guidance. As no artifacts due to overlying soft tissue are present, the joint surface can be imaged with high spatial resolution. Furthermore, ultrasound arthroscopy enables imaging of patella cartilage, which is not possible with external ultrasound imaging. Additionally, the IVUS system provides higher imaging resolution (spatial resolution of  $\sim 80 \mu\text{m}$ <sup>24</sup>) than the existing conventional clinical imaging modalities.

Articular cartilage thickness determined *in vitro* with an IVUS system has been shown to correlate strongly with the thickness determined with a reference ultrasound device.<sup>25</sup> This enables accurate scoring of cartilage lesions, unlike conventional arthroscopy which provides no information on cartilage thickness. Quantitative ultrasonic measurements of human articular cartilage have been conducted *in vivo* during arthroscopy,<sup>27-30</sup> and the potential of ultrasound arthroscopic imaging has been investigated in human knee joints.<sup>12</sup> However, the suitability of this technique for arthroscopy of the shoulder, a more restricted joint, has not been evaluated. In addition, the shoulder is a common site of chronic joint pain, and the third most common joint<sup>31</sup> to require surgical reconstruction after the knee and hip. The aim of this study is to evaluate the potential of quantitative high-frequency ultrasound arthroscopy for the diagnosis of cartilage defects in the human shoulder joint. Hence, we hypothesized that quantitative ultrasound arthroscopy is capable of detecting and grading articular cartilage defects in human shoulder joints *in vivo*.

## Patients and Methods

Nine patients (8 males, 1 female) undergoing shoulder arthroscopy were enrolled in the present study (**Table 1**). The average age of the patients was 52.8 (range 36-71) years. All measurements were done with permission from the National Agency for Medico-Legal Affairs, Helsinki, Finland (permission no.: Dnro103/13/03/02/09). Informed consents were also obtained from each patient. The study was in compliance with the guidelines of the host institution. Patients were examined clinically before arthroscopy and the shoulder joints were imaged with X-ray and MRI.

The indication for arthroscopy was longstanding shoulder pain, impingement syndrome or rotator cuff rupture. After routine shoulder arthroscopy, arthroscopic ultrasound examination was carried out using the same portals. Articular surfaces of the humeral head and glenoid were classified by the operating surgeon according to the International Cartilage Repair Society (ICRS) grading system<sup>32</sup> (**Table 2**).

Ultrasound imaging was performed using an IVUS catheter (diameter = 1 mm) consisting of a miniature unfocused high-frequency (40 MHz) ultrasound transducer attached to the tip of a rotating wire (30 rounds/s) and connected to a main measurement unit (ClearView Ultra, Boston Scientific Corporation, Boston, MA, USA). The ultrasound catheter was inserted into the shoulder joint through a shielding tube and directed to the location of interest on the articular surface under arthroscopic view. The proximal head of the humerus and glenoidal fossa of the scapula were evaluated (**Fig. 1**). Cartilage thickness was estimated based on the number of pixels between the surface and the cartilage-bone interface.

The space in the shoulder joint cavity is quite small, making it difficult to manipulate the catheter tip during arthroscopy. Because of the small distances, the possibility of error in locating the exact site for ultrasound imaging depended on lesion severity. In diffuse (broad) lesions, this error was a few millimeters; but in focal lesions, the measurement site was easily located with better accuracy under arthroscopic control. In sites with diffuse lesions, cartilage degeneration was graded based on region of interest on the joint surface, rather than a particular location, therefore minimizing the error in the arthroscopic grade of the measured site. During the procedure, ultrasound images and radiofrequency ultrasound signals were acquired from a total of 26 sites. Quantitative ultrasound parameters were calculated from the radiofrequency signals.

During signal acquisition, the angle of incidence between the articular surface and the direction of the ultrasound beam was adjusted manually in order to maximize the amplitude of the ultrasound reflection. This was done by observing the brightness of the articular surface on the monitor of the main unit. At every measurement site, three successive measurements were conducted and the best measurement (one with the best perpendicularity between the articular surface and the incident ultrasound signal) was chosen for calculation of the quantitative ultrasound parameters. Already established quantitative ultrasound parameters including ultrasound reflection coefficient ( $R$ ),<sup>14</sup> integrated reflection coefficient ( $IRC$ ),<sup>18</sup> apparent integrated backscatter ( $AIB$ ),<sup>18</sup> and ultrasound roughness index ( $URI$ )<sup>14</sup> were calculated offline using custom-made functions embedded in LabView software.<sup>33</sup>

In addition to the ultrasound data, digital video (**Fig. 1**) was recorded through the arthroscope (30°, diameter = 4 mm, Telecam SL PAL, Karl Storz GmbH, Tuttlingen, Germany).

**Table 1.** Descriptions of Patients Involved in the Study.

Patient No.	Sex, Age	Case History	Arthroscopic Findings
1	M, 50	Gradual progression of shoulder pain within 1 year with no preexisting trauma. Clinical presentation of AC arthrosis, subacromial impingement and SLAP lesion	Normal humerus and glenoid cartilage. Healthy rotator cuff
2	M, 61	Shoulder pain from 2006, especially at ROM above shoulder level. Partial relief with conservative treatment. MRI: subacromial bursitis, full thickness rupture and tendinosis of SSP tendon, tendinosis of SC tendon	Normal humerus and glenoid cartilage. SLAP 2 lesion, small rupture of SSP tendon, mild tendinitis of LHBB
3	F, 44	Shoulder pain for 1 year after fall, shoulder distension injury. Clinical presentation of SLAP and rotator cuff lesion. MRI: SLAP lesion and thin SSP tendon	Normal humerus and glenoid cartilage. SLAP 2 lesion, intact rotator cuff
4	M, 54	Shoulder pain for 2 years. No preexisting trauma. Clinical presentation of subacromial impingement and rotator cuff tear	Normal humerus and glenoid cartilage. Rupture of SSP tendon
5	M, 71	Bicycle accident 2 years prior with shoulder pain. Clinical presentation of rotator cuff tear and subacromial impingement. MRI: rupture of SSP tendon and downward pointing tip of acromion	Normal cartilage at centre and ICRS I-III lesions at periphery of humerus, superficial fibrillation (ICRS I) of glenoid. Rupture of SSP tendon
6	M, 36	Shoulder pain for 1 year after distorsion and shoulder luxation injury. Clinical presentation of rotator cuff pathology. X-ray: Hill Sachs lesion. MRI: intact labrum, LHBB, rupture of SSP tendon	Slight discoloration of cartilage, no fibrillation (ICRS I) on humerus. Normal glenoid cartilage. Remnant of LHBB and rupture. Rupture of SSP tendon
7	M, 36	Shoulder pain for 3 years. No preexisting trauma. Clinical presentation of AC arthrosis and subacromial impingement. MRI: same as Clinical presentation, with rupture of SSP tendon. Poor recovery with conservative treatment	Normal humerus and glenoid cartilage. SLAP I lesion, degenerative changes in SSP tendon, downward pointing tip of acromion
8	M, 61	6-year-old distorsion injury of right shoulder with limited abduction and flexion movements. Poor results with prolonged conservative treatment. Clinical presentation of rupture of SSP tendon, verified with MRI	Normal humerus and superficial roughness on glenoid cartilage. Rupture of the SSP tendon, SLAP I lesion
9	M, 63	Shoulder pain for 2 years without preexisting trauma. Clinical presentation of subacromial impingement. Unsatisfactory recovery with physiotherapy. MRI: rupture of SSP tendon	Normal humerus, and mostly normal glenoid cartilage with superficial fibrillation (ICRS I) at inferior part. SLAP I lesion, rupture of SSP tendon, downward pointing tip of acromion

AC = acromioclavicular; F = female; LHBB (tendon) = long head of biceps brachii (tendon); M = male; ROM = range of motion; SLAP = superior labral tear from anterior to posterior; SSP (tendon) = supra spinatus (tendon).

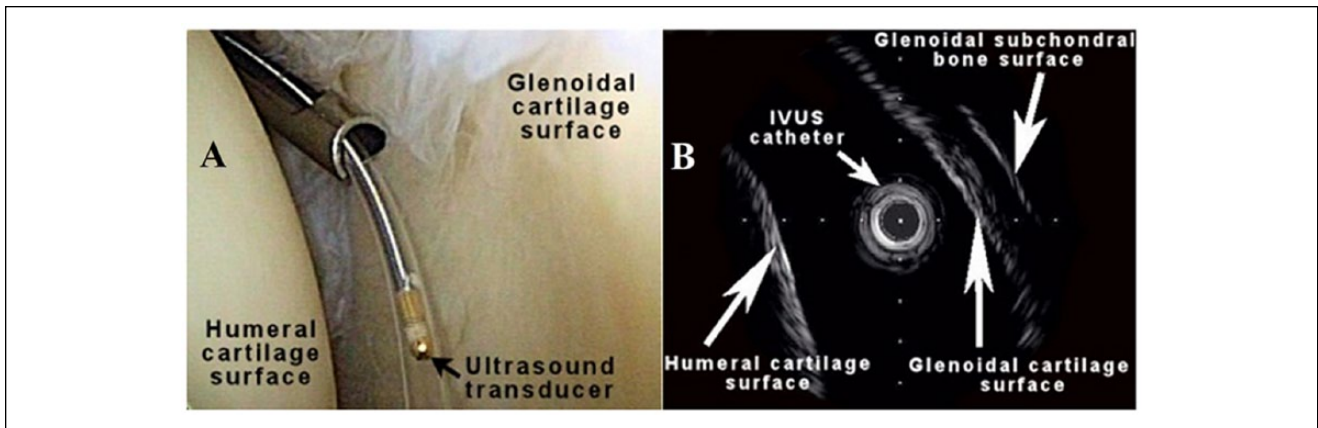
**Table 2.** Articular Cartilage Injury Classification According to International Cartilage Repair Society (ICRS).<sup>32</sup>

Grade	Description of Articular Cartilage Condition According to ICRS Grading System
0	Normal
1	Nearly normal. Superficial lesions. Soft indentation and/or superficial fissures and cracks
2	Abnormal. Lesions extending down to <50% of cartilage depth
3	Severely abnormal. Cartilage defects extending down >50% of cartilage depth as well as down to calcified layer and down to but not through the subchondral bone. Blisters are included in this grade
4	Severely abnormal. Cartilage defects extending through the subchondral bone

The video was used as reference to confirm the ICRS grade assigned to the cartilage surface at each site by the operating surgeon. The operating surgeon examined all 26 (blind coded) still ultrasound images and assigned ultrasound arthroscopy

scores to them according to the system summarized in **Table 3**.

This score had similar descriptions for cartilage condition as the ICRS grading (**Table 2**), excluding information



**Figure 1.** (A) The ultrasound catheter (left) was inserted into the glenohumeral joint through a portal under arthroscopic control. (B) Typical ultrasound image showing both humeral and glenoidal cartilage surfaces (right), imaging was optimized for glenoidal cartilage.

**Table 3.** Articular Cartilage Injury Classification According to the “Ultrasound Arthroscopy Score.”<sup>12</sup>

Grade	Description of Cartilage Condition According to the Ultrasound Arthroscopy Score
0	Normal
1	Nearly normal. Superficial lesions. Superficial fissures and cracks
2	Abnormal. Lesions extending down to <50% of cartilage depth
3	Severely abnormal. Cartilage defects extending down >50% of cartilage depth as well as down to calcified layer and down to but not through the subchondral bone. Blisters are included in this grade
4	Severely abnormal. Cartilage defects extending through the subchondral bone

on manual probing of cartilage. Presurgery 1.5-T MRI with routine clinical imaging sequences were available for patients 3 to 9 (Table 1). The MRI examinations for patients 1 and 2 were performed in a private clinic and results were not made available for this study, they were selected for arthroscopy based on history, symptoms, and clinical findings.

A radiologist evaluated and graded the cartilage at all the sites for the available patients. Grading of cartilage in the MR images was performed as described in Table 4.<sup>34</sup> A particular challenge encountered was associated with accurately matching the location where MR images were obtained with the location that was graded both visually and using ultrasound.

To address this, the measured locations were carefully described in the patient records. In addition, several MR images of each measured location were also taken. This information was used to find the corresponding location in

the MR images. ICRS scoring, MRI scoring, ultrasound arthroscopy, and calculation of ultrasound quantitative parameters were conducted by different members of the team blinded to the results of the other examiners.

### Statistical Analysis

Since the normality distribution test was not passed by the parameters ( $R$ ,  $IRC$ ,  $URI$ , and  $AIB$ ), ICRS grade, and ultrasound score were determined using the Spearman's correlation test. Statistical significance of differences between the degraded and intact sites was tested using the Mann-Whitney  $U$  test. The level of significance was set to  $P < 0.05$ . Statistical analyses were conducted with SPSS software (v. 15.0, SPSS Inc., Chicago, IL).

### Results

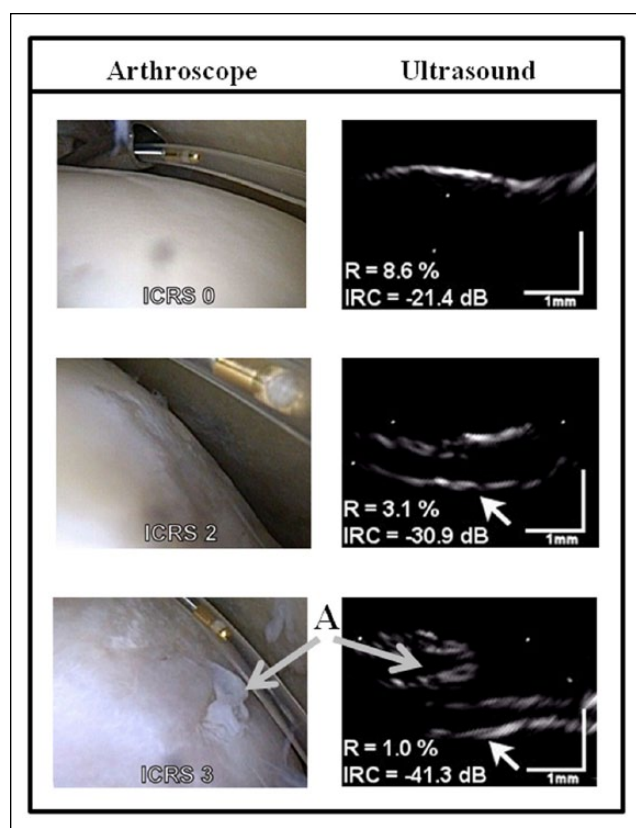
Arthroscopic ultrasound imaging of the shoulder joints revealed structures beneath the cartilage surface that were not visible in normal arthroscopic view. The subchondral bone layer was visible in all ultrasound images of sites with a lesion, making it possible to approximate cartilage thickness and hence the relative depth of lesions (Figs. 1 and 2). With visual evaluation during arthroscopy, 9 of the 26 measurement sites were assigned ICRS grades 1 to 3, while 17 sites were categorized as intact. With arthroscopic ultrasound, 12 of the 26 sites exhibited structural damage of the tissue and 14 were classified as intact. Arthroscopic ICRS grades and the ultrasound grades of the 26 evaluated sites were significantly correlated ( $r_s = 0.472$ ,  $P = 0.015$ ).

Values of ultrasound reflection parameters ( $R$  and  $IRC$ ) at sites with visually damaged cartilage surface ( $n = 9$ ) were lower than the values of intact cartilage ( $n = 17$ ) ( $P = 0.033$



**Table 4.** Evaluation of Articular Cartilage Defects From Magnetic Resonance Images.<sup>34</sup>

Grade	Description of Cartilage Condition According to the Intra-articular Ultrasound Score
0	Normal
1	Nearly normal. Superficial lesions. Superficial fissures and cracks
2	Abnormal. Lesions extending down to <50% of cartilage depth
3	Severely abnormal. Cartilage defects extending down >50% of cartilage depth as well as down to calcified layer and down to but not through the subchondral bone. Blisters are included in this grade
4	Severely abnormal. Cartilage defects extending through the subchondral bone

**Figure 2.** Representative arthroscopic and ultrasound images acquired from patient 5. Arthroscopic images show 1 intact (ICRS 0) and 2 damaged cartilage surfaces (ICRS 2 and ICRS 3). Ultrasound images demonstrate abnormalities of the articular surface. Cartilage is thin at the lesion sites (arrow indicates cartilage-bone interface). Loose cartilage fragment (A) can be observed in the ultrasound image (upper left quadrant of the subfigure).  $R$  and  $IRC$  decrease with increasing lesion severity. ICRS = International Cartilage Repair Society;  $IRC$  = integrated reflection coefficient;  $R$  = reflection coefficient.

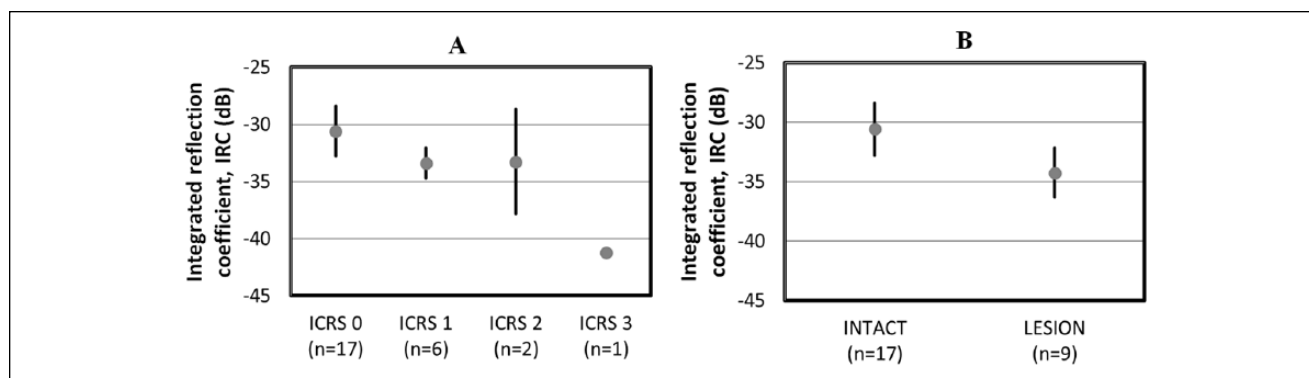
for  $R$ , and  $P = 0.043$  for  $IRC$ ). Surface roughness ( $URI$ ) and backscatter ( $AIB$ ) parameters measured at the damaged sites were not significantly different from those of intact tissue. Negative correlations were observed between the arthroscopic ICRS grade and  $R$  ( $r = -0.444$ ,  $P = 0.023$ ), and  $IRC$  ( $r = -0.426$ ,  $P = 0.03$ ) (Fig. 3). A slightly stronger negative correlation was observed between the “ultrasound score” and the reflection parameters ( $r = -0.546$ ,  $P = 0.004$  for  $R$ ; and  $r = -0.532$ ,  $P = 0.005$  for  $IRC$ ). MRI revealed grade 1 cartilage damage in only 2 of the available 7 patients. There was no significant correlation between the MRI grades and any of the parameters collected in this study.

## Discussion

In this study, we demonstrated for the first time the potential of using ultrasound arthroscopy for diagnostics of cartilage lesions and osteoarthritis in the human shoulder joint *in vivo*. In addition to acquisition of high-resolution ultrasound images, we determined qualitative and quantitative ultrasound parameters which correlated with the ICRS grading scores, as derived from conventional arthroscopy. Our results are consistent with earlier studies where this technique was tested *in vitro*,<sup>11,21</sup> in an animal joint *ex vivo*,<sup>35</sup> and *in vivo* in clinical arthroscopy of the human knee joint.<sup>12</sup>

Arthroscopic ultrasound was found to be more effective in detecting early stage cartilage damage compared to the 1.5 T routine clinical magnetic resonance imaging. MRI can provide a fairly accurate view of articular cartilage in the knee, where the tissue thickness is up to 4 mm. In the shoulder, however, articular cartilage is thinner, making evaluation with routine clinical MRI sequences more challenging. This may explain the lack of correlation between MRI data and the other parameters obtained in this study. Hence, arthroscopic ultrasound is a useful complementary technique for imaging and characterizing cartilage condition and lesions in the shoulder and possibly in other joints with relatively thin cartilage during conventional arthroscopy.

Quantitative ultrasound parameters were more effective in discerning the extent of cartilage damage than visual appraisal. The surface reflection parameters ( $R$  and  $IRC$ ) were significantly lower for damaged cartilage than for intact tissue, which is consistent with previous studies.<sup>12,35,36</sup> The “ultrasound score” yielded higher grades in 10, and lower grades in 2 out of the 26 cases compared to the ICRS grading. In 3 cases, cartilage injury could be detected with ultrasound, but not with conventional arthroscopy. This result is also in agreement with our earlier study on the potential of ultrasound arthroscopy for diagnosis of cartilage defect in the human knee joint *in vivo*,<sup>12</sup> where the “ultrasound score” was one rank higher than the ICRS grade



**Figure 3. (A)** Integrated reflection coefficient (IRC) versus ICRS grade determined by conventional arthroscopy. Ultrasound reflection at the articular surface (IRC) showed a decreasing trend with increasing ICRS grade ( $r = -0.426$ ,  $P < 0.05$ ). **(B)** Similarly, ultrasound reflection at lesion sites was generally lower than from the intact tissue (right) ( $P < 0.05$ ). The vertical bars indicate the 95% confidence interval. ICRS = International Cartilage Repair Society.

in 4 out of 13 cases.<sup>12</sup> These results suggest that the ultrasound data and images acquired during arthroscopy are more sensitive and accurate in grading the severity of cartilage lesions than visual appraisal.

As articular cartilage thickness cannot be easily judged visually, accurate and reliable arthroscopic scoring of lesions, particularly with regard to distinguishing between ICRS grades 2 and 3, is challenging even for experienced arthroscopic surgeons.<sup>1</sup> Ultrasound arthroscopy overcomes this problem by providing information on cartilage thickness.<sup>12,35</sup> In this study, it was possible to visualize in real-time the full depth of the cartilage and also the cartilage-bone interface from the arthroscopic ultrasound images of sites with lesions, enabling accurate estimation of lesion depth. This was useful in discriminating between ICRS grades 2 (cartilage >50% of intact thickness) and 3 (cartilage <50% of intact thickness) lesions, thus aiding and improving the accuracy of lesion scoring. In practice, it is uncommon for patients with mild arthritis to require treatment, those with osteoarthritis do not typically go for treatment until they are in advanced stages at which point arthroplasty is required. Nevertheless, the technique presented in this study is significant because it can supplement conventional arthroscopy as a real-time guiding tool during removal of damaged tissue and also help in the estimation of cartilage thickness during sensitive procedures such as abrasion arthroplasty.

In this clinical study, certain technical challenges associated with positioning of the catheter during imaging were observed, and these need to be solved prior to routine clinical application of ultrasound arthroscopy. First, it was time-consuming to find the correct position and angle of the catheter for optimal measurement of quantitative ultrasound parameters. This increased the operation time by an average of 15 minutes. Since the safety and convenience of the patient is of utmost priority, a more effective ultrasound catheter designed and optimized for arthroscopy would

need to be developed. This is a subject of ongoing research in the group. Furthermore, since this was a feasibility study, the intra- and interobserver reliability were not investigated. Thus, this requires further investigation.

The high-frequency ultrasound transducer (central frequency of 40 MHz) used in this study enabled acquisition of high-resolution images of the tissue, but to a limited depth. Because of this depth of penetration limitation, ultrasound at this frequency may not penetrate to the cartilage-subchondral bone interface in thick human cartilage. This makes the measurement of cartilage thickness challenging in intact (and thick) cartilage. To overcome this challenge, an ultrasound catheter with a lower frequency transducer, such as the 9 MHz transducer used by Liukkonen *et al.*<sup>22</sup> may be useful for quantitative evaluation of the properties of subchondral bone. This could provide important diagnostic information about conditions such as subchondral sclerosis that is often consistent with the early stages of osteoarthritis.<sup>37,38</sup> However, the greater penetration of the lower frequency transducer comes at the cost of lower image resolution.

A possible solution to obtain both high-resolution imaging and better penetration to the subchondral bone may be realized by using a custom-made intermediate frequency transducer. An alternative solution for high-resolution imaging of articular cartilage is via optical coherence tomography (OCT).<sup>39</sup> However, the penetration depth of OCT is approximately 1 mm into cartilage, making visualization of the subchondral bone plate in a healthy joint with thick cartilage impossible. Nevertheless, combining OCT and ultrasound in the same arthroscopic instrument could provide important information for the diagnosis of joint pathologies. Furthermore, objective evaluation of articular cartilage structure and pathology is of immense importance if indications for cartilage repair and also the quality of the repair tissue are to be evaluated *in vivo*. Arthroscopic ultrasound provides a promising technique for achieving this objective.

In conclusion, ultrasound arthroscopy of the shoulder joint can provide quantitative diagnostics on the severity of cartilage lesions. Furthermore, the diagnostic potential of conventional arthroscopy can be enhanced by quantitative arthroscopic ultrasound imaging.

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### Declaration of Conflicting Interests

The Author(s) declare(s) that there are no conflicts of interest.

### Ethical Approval

All measurements were done with permission from the National Agency for Medico-Legal Affairs, Helsinki, Finland (Permission No. Dnro103/13/03/02/09).

### Informed Consent

Written informed consent was obtained from all subjects before the study.

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